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MODELING OF PHASE TRANSFORMATION KINETICS OF PLAIN CARBON STEEL

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF

Bachelor of Technology
in
Metallurgical and Materials Engineering

By
ANIRUDDHA CHATTERJEE
&
BISWARANJAN DASH

Department of Metallurgical and Materials Engineering
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Under the Guidance of

Prof. B.C.RAY

Department of Metallurgical and Materials Engineering
National Institute of Technology
Rourkela

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Department of Metallurgy and Materials Engg..
N.I.T Rourkela,
May 12th, 2009

Aniruddha Chatterjee
Roll No-***10504031***,
8th *Semester.*
B.Tech-***Part (IV)***

ABSTRACT.

A mathematical model have been generated which incorporates the concept of isothermal/isokinetic steps in close association with the cooling curve to predict the transformation kinetics under continuous cooling conditions. Transformation kinetics under actual cooling conditions was predicted by the dilatometric analysis of the 1080 steel samples. The continuous cooling experiments were conducted for cooling rates of 5, 10, 15, 20^0 K/min to determine the time and temperature for start and end of pearlitic transformation respectively. The isothermal transformation data was also incorporated in the mathematical model to predict the continuous cooling transformation kinetics. The results of the mathematical model agree closely and in a similar manner with the measurements made at the four cooling rates.

CONTENTS

1. INTRODUCTION.

The steel industry is rapidly adopting continuous processes including continuous casting, continuous annealing and continuous heat treatment to minimize production costs, to save time and to improve product quality. The prediction of phase transformations in heat-treatment processes such as controlled cooling of wire rod is made difficult by the complex nature of coupled heat transfer and phase transformation kinetics. Heat transfer at the surface of the metal, for example, depends upon local cooling conditions which change with temperature, fluid properties and relative fluid velocity. Within the metal, the thermo-physical properties changes with temperature and the heat of transformation is released. The factors which affect transformation kinetics are cooling rate, prior-austenitic grain size, and steel composition. Thus, the problem of transformation kinetics under non-isothermal conditions is of tremendous practical importance. However, experimental and theoretical aspects of the decomposition are most conveniently studied isothermally. So it is desirable to relate the transformation behavior of steel under continuous cooling with its isothermal transformation data.

The isothermal transformation diagram is a valuable tool for studying the temperature dependence of austenitic transformations. Information of a very important and practical nature can be obtained from a series of isothermal reaction curves determined at a number of temperatures. Even in a single, such as austenite to pearlite transformation, the product varies in appearance with the transformation temperature. The simplest one is the TTT curve for eutectoid steel. From this plot, the time required to start the transformation and the time required to complete the transformation may be obtained. This is done in practice by observing the time to get a finite amount of transformation product, usually 1 percent, corresponding to the start of the transformation. The end of the transformation is then arbitrarily taken as the time to transform 99 percent of the austenite to pearlite.

On the other hand a continuous cooling transformation curve gives us idea about austenitic transformations under continuous cooling conditions i.e. transformation kinetics under different cooling rates. Since most of the transformations occur in continuous cooling conditions, CCT curves are more of importance than the TTT curves.

The picture becomes clearer if we superimpose different cooling rates upon the CCT curve to identify the time to start transformation i.e. 1 percent of transformation product and time to end transformation, usually 99 percent of transformation product.

There have been several attempts to predict the cooling transformation from an experimentally determined set of isothermal transformation curves. The initial work in this direction was carried out by **Prakash K.Aggarwal and J.K. Brimacombe** (1) whose model consists of heat flow equations and transient distribution of temperature and fraction transformed can be predicted simultaneously. **Scheil**, (2) and later **Steinberg**, (3) presented an additivity rule for calculating the temperature at which transformation begins during continuous cooling. An additive reaction implies that the total time to reach a specified stage of transformation is by addition of fraction of time to reach this stage isothermally until the sum reaches unity. Most of the previous studies have been limited to the beginning of the transformation and not many work (4-7) have been carried out about the continuous cooling transformation over the entire range of reactions.

In the present work an attempt will be made to model the transformation kinetics for austenite to pearlite transformation for 1080 eutectoid steel under continuous cooling conditions using the isothermal transformation data. Apart from that prediction of continuous cooling transformation kinetics will be carried out under the effect of factors such as prior-austenitic grain size, deformation, cooling rates etc.

2. THEORY.

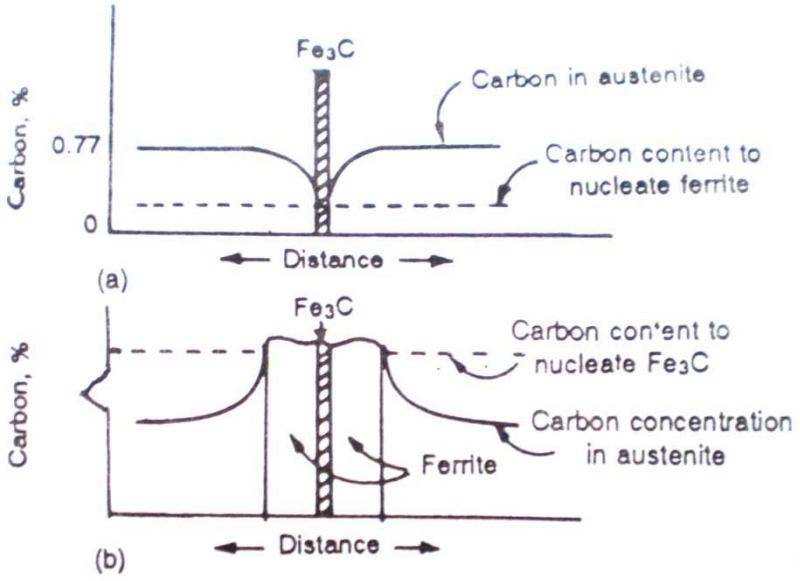
2.1 Austenite → Pearlite Transformation.

The most famous and commercially important transformation occurs at 0.77%wt C known as **eutectoid transformation**. Today fully pearlitic steels are of great importance in a number of extremely demanding structural applications. Fully pearlitic carbon steels are used in a number of important applications where high strength, wear resistance, ductility, toughness, and low cost are important. Chief among such applications are high-strength wires and high-strength tee rails. When eutectoid steel is heated to the austenising temperature and held there for a sufficient time, the structure will become homogenous austenite. On very slow cooling under conditions approaching equilibrium, the structure will remain that of austenite until just above the eutectoid temperature .At the eutectoid temperature or just below it, the entire structure of austenite will transform into a lamellar product called pearlite which consists of alternate layers of ferrite and cementite. The region in which ferrite and cementite plates are parallel to one another is called a colony. However, different pearlite colonies have different lamellar orientation, and, as the transformation progresses, neighboring colonies join together and continue to advance into the austenite, such that when transformation occurs at lower degrees of undercooling, the colony group's advance in a roughly spherical boundary leading to the formation of a nodule.

2.2 Transformation Mechanism.

Pearlite is a lamellar product of eutectoid decomposition which can form in steels during transformation under isothermal, continuous-cooling, or forced velocity **(8, 9)** (directional) growth conditions. The austenite to pearlitic transformation occurs by nucleation and growth. Nucleation mostly occurs heterogeneously almost exclusively at the grain boundaries of austenite, if it is homogenous, otherwise also at carbide particles, or in the region of high carbon concentration, or on the inclusions, if present. The nucleated pearlite then grows into the austenite as roughly spherically shaped nodules as seen in the microstructure.

2.2.1 Hull-Mehl model (10) for pearlitic transformation shows that initial nucleus is a widmanstatten platelet of cementite, which forms at the austenite grain boundary to grow into one of the austenite grains. As this thin small plate grows in length, it thickens as well. It occurs by the removal of carbon atoms from austenite on both sides of it till carbon decreases in the adjacent austenite to a fixed low value at which ferrite nucleates, which then grows along the surface of the cementite plate. The growth of ferrite (C~0 %) leads to the buildup of carbon at the ferrite-austenite interface, until there is enough carbon to nucleate fresh plates of cementite, which then grow. This process of formation of alternate layers of ferrite and cementite forms a colony. A new cementite nucleus of different orientation may from at the surface of colony which leads to the formation of another colony. In a given colony the ferrite and cementite plates share a common orientation. Then the colonies advance into the untransformed austenite in the spherically shaped structures which are called nodules.



Nucleation of Ferrite and Cementite in growing Pearlite

2.3 Nucleation and Growth.

The transformation and growth mechanism in general was predicted by an extensive study carried out by **Melvin Avrami. (11)**. The general theories of phase change with the following assumptions strongly supported with experiment are:-

(1) The new phase is nucleated by tiny "germ nuclei" which already exist in the old phase and whose effective number $\bar{N}$ per unit nucleation region can be altered by temperature and duration of superheating. These germ nuclei, which may be heterogeneities of any sort, usually consist of small particles of the subcritical phase or tough films of the latter surrounding foreign inclusions.

(2) The number of germ nuclei per unit region at time t, $N \equiv N(t)$ decreases from $\bar{N}$ in two ways: (a) through becoming active growth nuclei with number $N' \equiv N'(t)$, as a result of free energy fluctuations with probability of occurrence ***n*** (a function of temperature, concentration, etc.) per germ nucleus; (b) through being swallowed by grains of the new phase whose linear dimensions are growing at the rate ***G*** (also a function of temperature, concentration, etc.). Letting

$V \equiv V(t)$ represents the volume of the new phase per unit volume of space we are led to the relation:-

$$N(t) = \bar{N} e^{-nt}[1 - V(t)]$$

between the density of the germ nuclei and transformed volume. For the density of growth nuclei

we find

$$N'(t) = \bar{N} \int_0^t e^{-nz}[1 - V(z)]dz.$$

(3) If now it is assumed, as is plausible from the underlying mechanisms and as the experiments verify, that

G/n==α,

is approximately independent of temperature and concentration in a given "isokinetic range" for a given substance and crystal habit, we have,

$$V_{m\ ex} = \int_0^{\tau} N(z_1)dz_1 \int_0^{z_1} N(z_2)dz_2 \cdots$$

$$\times \int_0^{z_{m-1}} N(z_m)\bar{v}_m[\alpha(\tau - z_1), \cdots \alpha(\tau - z_m)]dz_m.$$

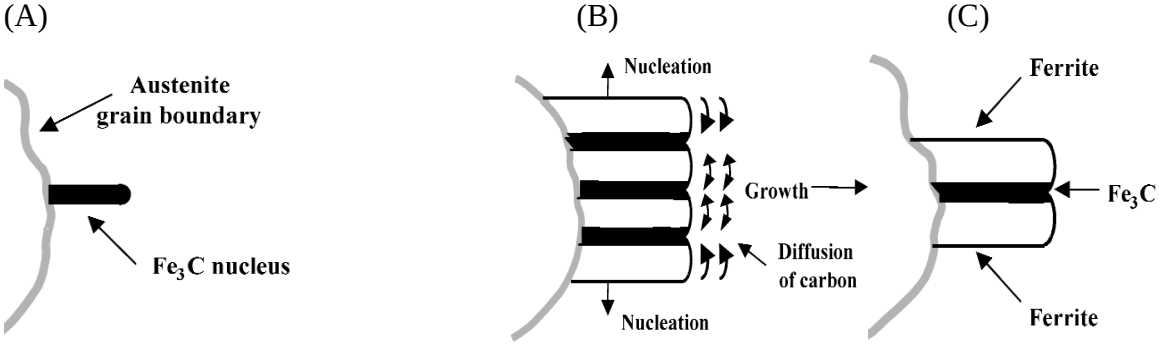
In particular,

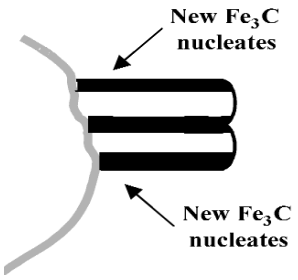
$$V_{1\ ex} = \sigma\alpha^3 \int_0^{\tau} (\tau - z)^3 N(z)dz,$$

for psuedospherical or polyhedral grains, where σ is the shape factor and is equal to 4π/3 for spherical grains.

Melvin Avrami had shown that the relative internal history of the transformation is independent of temperature, concentration, or other variables (the range in which ***n*** and ***G*** are proportional); or to restate our conclusion: ***For a given substance and crystal habit, there is an "isokinetic range "of temperatures and concentrations throughout which the kinetics of phase change in the characteristic time scale remains unchanged***.

According to **Hillert, (12)** the possible sites for nucleation of pearlite may be either ferrite or cementite on an austenitic grain boundary. In hypereutectoid steel, cementite will nucleate first and in case of hypoeutectoid steel, ferrite will nucleate first. In case of eutectoid steel **(13)** there is initial competition between the two phases to nucleate first and then the other forming a film on the other until there is alternate structure of pearlite. **Nicholson**, **(14)** in analyzing kinetic data for the formation for pearlite, has also emphasized that ferrite can nucleate first in hypoeutectoid steel. **Mehl and Hagel (15)** proposed the formation of pearlite nodules by sideways nucleation and edgeways growth into the austenite.

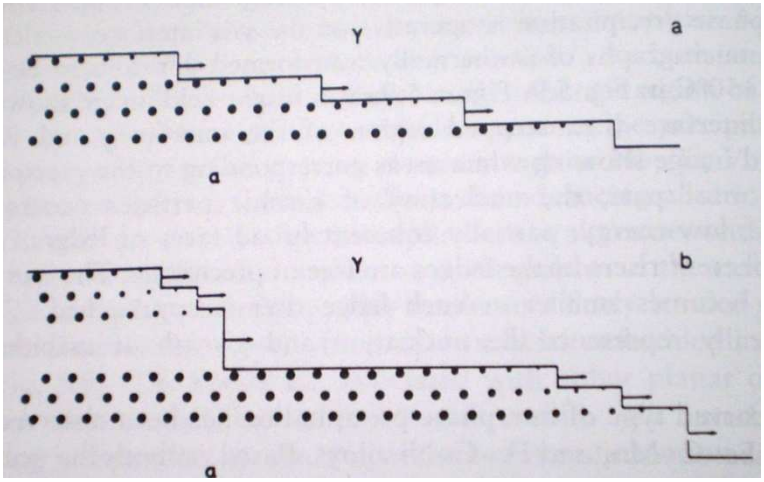




(D)

Schematic representation of pearlite formation by nucleation and growth-(A) through (D)

Modin (16) and **Hillert (12)** first showed that the proeutectoid phase can be continuous with the same phase present in the pearlite. Recent work by **Honeycombe** and **Dippennar (17)** showed conclusively that nucleation of pearlite occurred on grain boundary cementite and there is continuity of grain boundary and pearlitic cementite. They have therefore confirmed earlier observations of Hillert that in pearlite sideways growth occurred as a result of branching mechanism rather than by repeated nucleation. That is all the cementite lamellae were branches of one stem of the cementite branch which had grown out from the cementite network. The necessary criterion for the cooperative growth of ferrite and cementite in pearlite is that they should have an incoherent interface with the austenite. However, **Hackney and Shiftley (18, 19)** showed that the advancing pearlite is partially coherent with the austenite and migrates with lateral movement of steps.



Schematic planar interphase precipitation showing (a) uniform steps (b)irregular steps

Hence pearlite reaction occurs by ledgewise cooperative growth and the essential conditions are:

$$G_{\alpha} = G_{cm}$$

$$h_{\alpha}/\lambda_{\alpha} = h_{cm}/\lambda_{cm}$$

where **G**'s are the growth rates, **h**'s are the ledge heights, and **λ**'s are the interledge spacing for the respective phases.

For pearlitic growth, the important parameters are pearlitic growth rate **G** (into the austenite) and the interlamellar spacing, which are assumed to be constant for a given temperature.

The **Zener-Hillert (20, 21)** equation for pearlitic growth, **G**, (1) the super saturated austenite is in local equilibrium with the constituent phases of the pearlite at the reaction front. (2) Volume diffusion of the carbon in austenite is rate controlling.

The equation, relating the growth and interlamellar spacing is:-

$$G = \frac{D^{\lambda}_{c} . S^{2}}{K \ \lambda^{\alpha} \lambda^{cm} (C^{cm}_{c} - C^{\alpha}_{c})} . \frac{(C^{\gamma\alpha}_{c} - C^{\gamma cm}_{c})}{} . 1/S.(1-S_c/S)$$

Where D^{λ}_{c} is the volume diffusivity of carbon in austenite;

k is the geometric parameter (~0.72 for Fe-C eutectoid alloy)

$C^{\gamma\alpha}_{c}$ and $C^{\gamma cm}_{c}$ are the carbon concentration in the front of the ferrite and cementite lamellae.

C^{α}_{c} and C^{cm}_{c} are the respective equilibrium concentrations of carbon within the ferrite phase and cementite phase.

λ^{α} and λ^{cm} are the respective thickness of ferrite and cementite lamellae.

S is the interlamellar spacing.

S_c is the interlamellar spacing when the growth rate becomes zero.

Zener (20) proposed the maximum growth criterion to stabilize the system is given by :

$$S = 2S_c$$

Using this relation the equation relating the critical spacing and undercooling, **ΔT**, for isothermal and continuous cooling transformation is given by

$$S_c = \frac{2\gamma^{\alpha cm} . T_E}{}$$

$$\Delta H_v \cdot \Delta T$$

where $\gamma^{\alpha cm}$ is the interfacial energy of the ferrite/cementite lamellar boundary in pearlite.

ΔH_v is the change in enthalpy per unit volume.

Combining the above two equations we have

$$S = S_c = \frac{4\gamma^{\alpha cm} \cdot T_E}{\Delta H_v \cdot \Delta T}$$

A. M. Elwazri*1, P. Wanjara2 and S. Yue (22) in their work had found a relation between transformation temperature or degree of undercooling on interlamellar spacing. It is given as:

$$S = \frac{7.5}{(T_E - T)}$$

Where

T_E is the Eutectoid temperature and **T** is the transformation temperature.

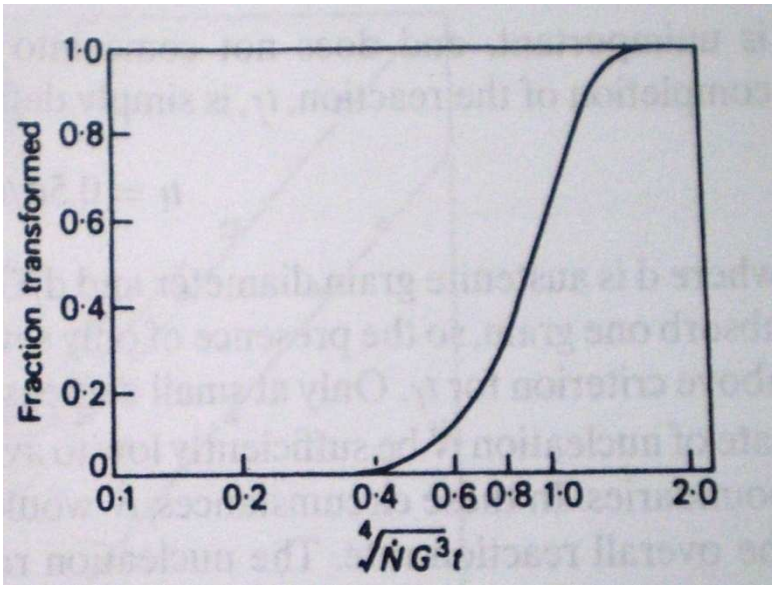
O'Donnelly (23) in his work had predicted the relation between thickness of the cementite lamellae t_c as a function of C% of the steel as

$$t_c = \frac{S^* 0.15(wt\%\ C)}{V}$$

Pearlite nodules usually nucleate on the austenite grain boundaries and grow at a constant radial velocity into the surrounding grains. At temperatures immediately below A_1, where the N/G ratio is small, the nucleation of very few nodules is possible and they grow as spheres without interfering with one another. Accordingly the following time-dependant reaction equation due to **Johnson and Mehl (24)** applies:

$$f(t) = 1 - e^{-(\pi/3)N.G\hat{}3.t\hat{}4}$$

Where **f (t)** is the volume fraction of pearlite formed isothermally at a given time **t**; **N** is the nucleation rate, assumed to be constant; and **G** is the growth rate. If the rate of nucleation is higher due to large undercooling the austenitic grain boundary becomes covered with pearlite nodules prior to the transformation of significant fraction of austenite. Transformation simply proceeds by thickening of these pearlite layers into the grains **(25, 26)**.



Master reaction curve for general nucleation (**Johnson and Mehl**)

The morphology changes as the rate of cooling increases, from a spherical model to hemispherical model because:

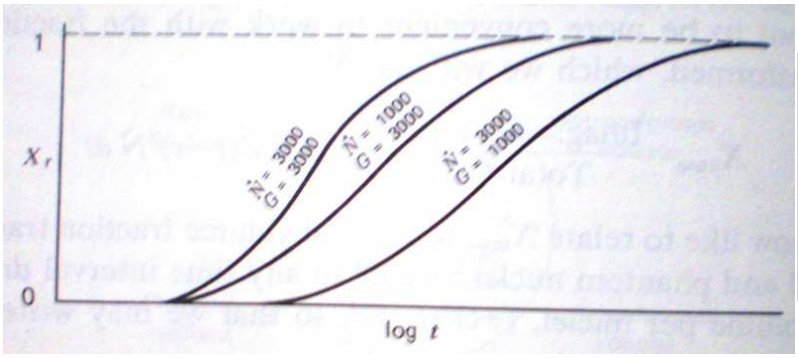
(1) Random nucleation does not occur.

(2) **N** is not constant but a function of time.

(3) **G** also varies with time and from nodule to nodule.

(4) The nodules are not spheres.

Once again coming back to the above mentioned **Johnson-Mehl equation** is applicable to any phase transformation subject to the four restrictions of random nucleation, constant **N**, constant **G**, and a small **τ.** Many solid-state phase transformations nucleate at grain boundaries so that a random distribution of nucleation does not occur. A plot of the Johnson-Mehl equation is shown in the figure below for different values of growth rate **G** and the nucleation rate **N. (27)**



A plot of the Johnson-Mehl equation for various values of **G** and **N.**

These curves demonstrate the obvious fact that the volume fraction transformed is a much stronger function of **G** than of **N**. These curves are said to have a sigmoidal shape, and this shape is characteristic of nucleation and growth transformations.

It is often found that the growth rate **G** is a constant but nucleation rate **N** is usually not constant in solid-solid phase transformations, so that one would not expect the previous **Johnson-Mehl** equation to be strictly valid. **Avrami** considered the case where the nucleation rate decayed exponentially with time. Consequently **Avrami (28)** applied the following time dependant reaction equation:

$$f(t) = 1 - e^{-kt^{\wedge}n}$$

where **k and n** are both temperature dependant parameters.

n varying from 1 to 4 is a quantity dependant on the dimension of growth. **(29)**

Cahn and Hagel (15) have further developed special cases for Avrami equation by predicting constants for various nucleation sites, namely, grain faces, grain edges and grain corners.

Nucleation site	k	n
Grain boundary	**2AG**	1
Grain edge	**πLG^2**	2
Grain corner	**4π ηLG^3**	3

where: **G** is the growth rate, **A** is the grain boundary area, **L** is the grain edge length, and **η** is the number of grain corners per unit volume.

The nucleation rate **N** is irrelevant in all the three cases because all the grain boundaries at which pearlite transformation can take place has been transformed. Transformation by site saturation occurs when the pearlite nodules migrate half way across the grain. Hence the time given for the complete transformation is given by:-**[15]**

$$t_f = 0.5\frac{d}{g}$$

Where **d** is the average grain diameter, **G** is the average growth rate of pearlitic growth, and'**d/g**' is the time taken for on nodule to transform to one austenitic grain.

In eutectoid steel, **N** would have no effect below about 660°C while in hypereutectoid steels; the overall rate would be independent of **N** below 720°C **(15)**. At these temperatures, **N**, where measured, appears to increase with time according to the following equation:

$$N = a.t^m$$

Where **a** and **m** are constants. **Cahn** found the time exponent **m** in the Avrami equation to be just **4+m** and to be a function of grain boundary area for grain boundary nucleation.

Avrami equation is valid for only **isothermal** cases of transformation of austenite to pearlite. The equation relating the **non-isothermal transformation (30)** from austenite to pearlite is given as

$$x = 1 - \exp \int_{Ac_1}^{T} \frac{4\pi}{3\dot{T}^4} \dot{N} G^3 \Delta T^3$$

Roosz et al. (31) determined the temperature and structure dependence of and **G** as a function of the
reciprocal value of overheating (**DT = T-Ac1**),

$$\dot{N} = \frac{1.378 \times 10^{-12}}{\left[\left(a^p\right)^2 \sigma_o\right]^2} \exp\left(\frac{-25.38}{T - Ac_1}\right) \qquad \frac{1}{\mathrm{mm}^3 s}$$

and

$$G = \frac{7.0 \times 10^{-11}}{{\sigma_o}^2} \exp\left(\frac{-29.7}{T - Ac_1}\right) \qquad \frac{\mathrm{mm}}{s}$$

where $\dot{N}$ and **G** are function of temperature. The integral within the exponential was evaluated numerically. The eutectoid temperature **Ac1** of the steel was obtained using **Andrews' formula. (32).**

2.4 FACTORS AFFECTING PEARLITIC TRANSFORMATION

2.4.1 Austenitic grain size

If the austenisation temperature is lower i.e. around 800°C, the austenite grains are finer. On the contrary, if the austenisation temperature is higher i.e. around 1200°C, the austenitic grain size is larger. Austenite to Pearlitic transformation initiates at the grain boundary. Hence, in case of finer grains, the total grain boundary available for transformational kinetics is greater than the coarse grains.

2.4.1.1 Effect on Pearlitic nodule size

Hull et' al (33, 34) have reported that the nucleation rate of pearlite, hence nodule diameter, is very sensitive to the variation in prior-austenitic grain size. Therefore, for a specific transformation temperature, which dictates the number of nucleation sites for pearlite transformation, the nodule size should be directly related to prior-austenitic grain size. **(35)**. The dependence of the nodule size on the transformation conditions is most likely linked to the increase in prior-austenitic grain size. **Marder and Bramfitt (36)**.have shown through cinephotomicrography using a hot-stage nodules nucleate only at the austenitic grain boundaries.

2.4.1.2 Effect on Pearlitic colony size

A.M.Elwazri, P Wanjara and S.Yue in their work had observed change in pearlitic colony size with prior austenitic grain size was within the 0.6 nm error in size measurement, a negligible effect was concluded for all the hypereutectoid steels investigated. This finding is in agreement with previous work by **Pickering and Garbarz (37)** who have reported too that the prior-austenitic grain size affects the morphology of pearlitic nodules rather than the size of the colonies. **Garbarz and Pickering (38**) have shown that the dependence of the pearlite colony size on the transformation temperature is similar to that of the interlamellar spacing variation with the transformation conditions.

2.4.1.3 Effect on interlamellar spacing

The size of the interlamellar spacing increases slightly as the austenisation temperature or prior-austenitic grain size was increased. **(22)**. The same effect of prior-austenitic grain size on the interlamellar spacing was also supported by **Modi et al (39)** on an eutectoid steel composition that have reported an increase of 0.07µm in the spacing owing to an increase in the austenisation temperature from 900 to 1000°C.in general, this secondary influence of the prior austenite grain size on the pearlitic interlamellar spacing can be reasoned on the basis of the total grain boundary area, which decreases as the grain size increases on account of the reduction in the nucleation sites for the ferrite and cementite phases. In particular, as pearlite nucleation mainly occurs on the prior austenitic grain corners, edges and surfaces, the density of the nucleation sites, which is directly related to grain size, for ferrite and cementite phases is reduced with increasing austenite grain size and thereby contributes to increase interlamellar spacing. **(39)**

2.4.2 COOLING RATE

2.4.2.1 Effect on interlamellar spacing

The effect of cooling rate on the interlamellar spacing pearlitic spacing has mainly attributed to the fact that they have an effect on the phase transformation temperature from austenite to pearlite. As the cooling rate increases, the phase transformation supercooling also increases, thus the phase transformation A_{r3} from austenite to pearlite decreases. It is well known that it becomes difficult for carbon elements to diffuse at

lower temperatures, so the pearlite with thin spacing precipitates. **J.H. Ai., T.C. Zhao, H.J. Gao, Y.H. Hu, X.S. Xie(40)** in their work had obtained same results as far as the variation of interlamellar spacing with cooling rate is concerned. **Marder and Bramfitt (41)** have shown, in the case of the eutectoid steel that the interlamellar spacing of cementite is practically the same when the transformation takes place by continuous cooling as when it takes place under isothermal conditions. During continuous cooling, the cooling rate determines the temperature at which the reaction starts. The transformation then is going on at practically constant temperature because of recalescence.

Effect of interlamellar spacing on hardness.

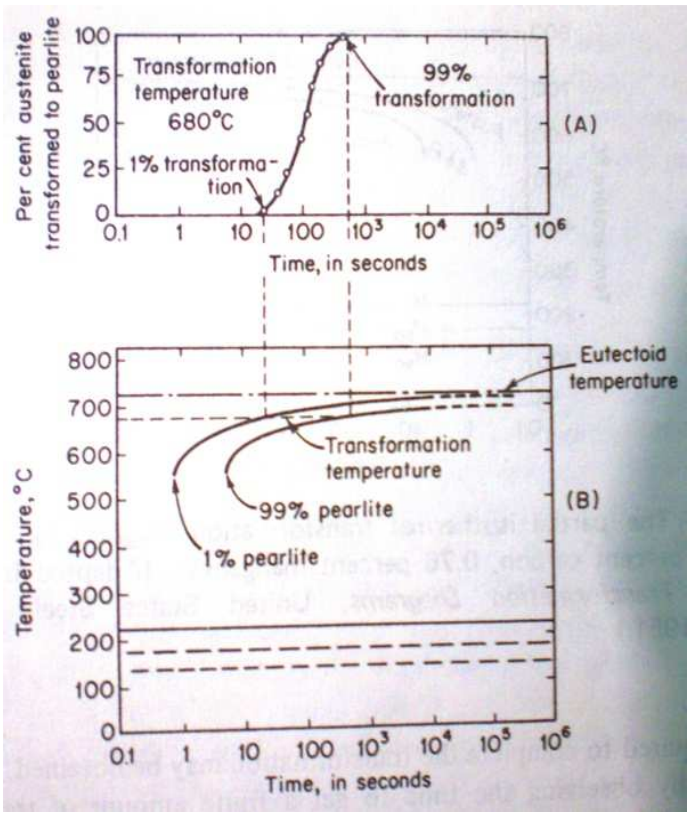
The strength of pearlite would be expected to increase as the interlamellar spacing is decreased. Early work by Gensamer and colleagues showed that that the yield stress of a eutectoid plain carbon steel, i.e. fully pearlitic, varied inversely as the logarithm of the mean free ferritic path in the pearlite.

2.4.2.2 Effect on pearlitic colony size

With the increase in the cooling rate, the colony size should decrease because the transformational kinetics, i.e. nucleation and growth increases. As a result of which finer colony size is expected. A similar relation was obtained by **Ghasem DINI, Mahmood Monir Vaghefi and Ali Shafyei in their work. (42)**

2.5 TIME-TEMPERATURE-TRANSFORMATION CURVES.

Information of very important and practical nature can be obtained from a series of isothermal reaction curves determined at a number of temperatures.**(43)**



In the adjacent figure as shown aside the experimental counterparts of plot (A) can be obtained by isothermally reacting an number of specimens for different lengths of time and determining the fraction of the transformation product in each specimen. From the reaction curve the time required to start the transformation and the time required to complete the transformation may be obtained. This is done in practice by observing the time to get a finite amount of transformation, usually 1%, corresponding to the start of transformation. The end of transformation is then arbitrarily chosen as the time to transform 99% of austenite to

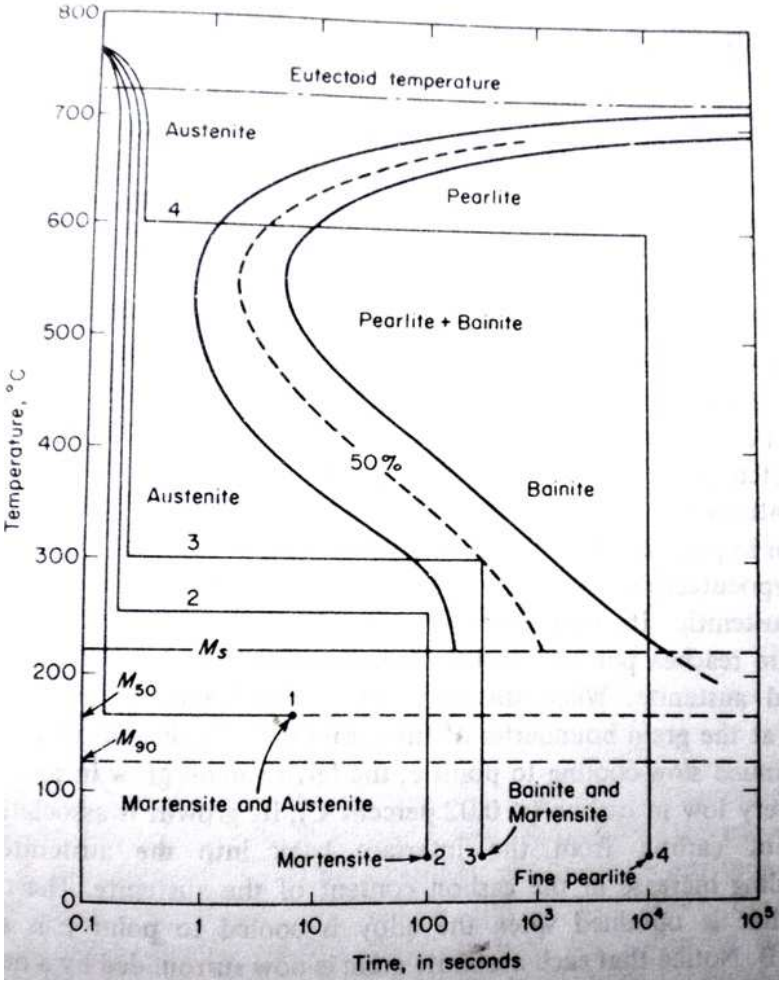
(A) Reaction curve for isothermal formation of pearlite.(B)T-T-T diagram obtained from reaction curves.(adapted from ***Atlas of Isothermal Transformation Diagrams***.)

Pearlite. A plot of the transformation data at different temperatures is combined to obtain (B). One of the significant features about the pearlitic transformation is the short time required to form pearlite at around 600ºC. The time-temperature-transformation (T-T-T) diagram corresponds only to the reaction of austenite to pearlite. It is not complete in the sense that the transformations of austenite, which occur at temperatures below about 550ºC, are not shown. Hence it is necessary to consider other type of austenitic reactions: austenite to bainite and austenite to martensite.

The time-temperature-transformation (T-T-T) diagram is once again shown below. However, the curves corresponding to the start and finish of transformation are extended into the range of temperatures where austenite transforms to bainite. Because the pearlite

and bainite transformations overlap in simple eutectoid iron-carbon steel, the transition from pearlite to bainite reaction is smooth and continuous. Above approximately 550 ºC to 600 ºC, austenite transforms completely to pearlite. Below this temperature to approximately 450 ºC, both pearlite and bainite is formed. Finally, between 450 ºC and 210 ºC, the reaction product is bainite only.

The significance of the dotted lines running in between the beginning and end of isothermal transformations represents 50% transformation.



. ***The complete T-T-T curve for an eutectoid steel showing arbitrary time-temperature paths on the isothermal transformation diagram***

Let us consider the paths mentioned as 1, 2, 3, and 4.

Path 1:- the specimen is cooled rapidly to 160 ºC and left there for 20 min. The rate of cooling is too rapid for pearlite to form at higher temperatures, therefore the steel remains in austenitic phase until **Ms** temperature is passed, where martensite begins to form athermally.160 ºC is the temperature at which half of the austenite transforms to martensite. Holding at 160 ºC forms only a very limited amount of additional martensite because in simple carbon steels isothermal transformation to martensite is very minor. Hence at point 1, accordingly, the structure can be assumed to be half martensite and half retained austenite.

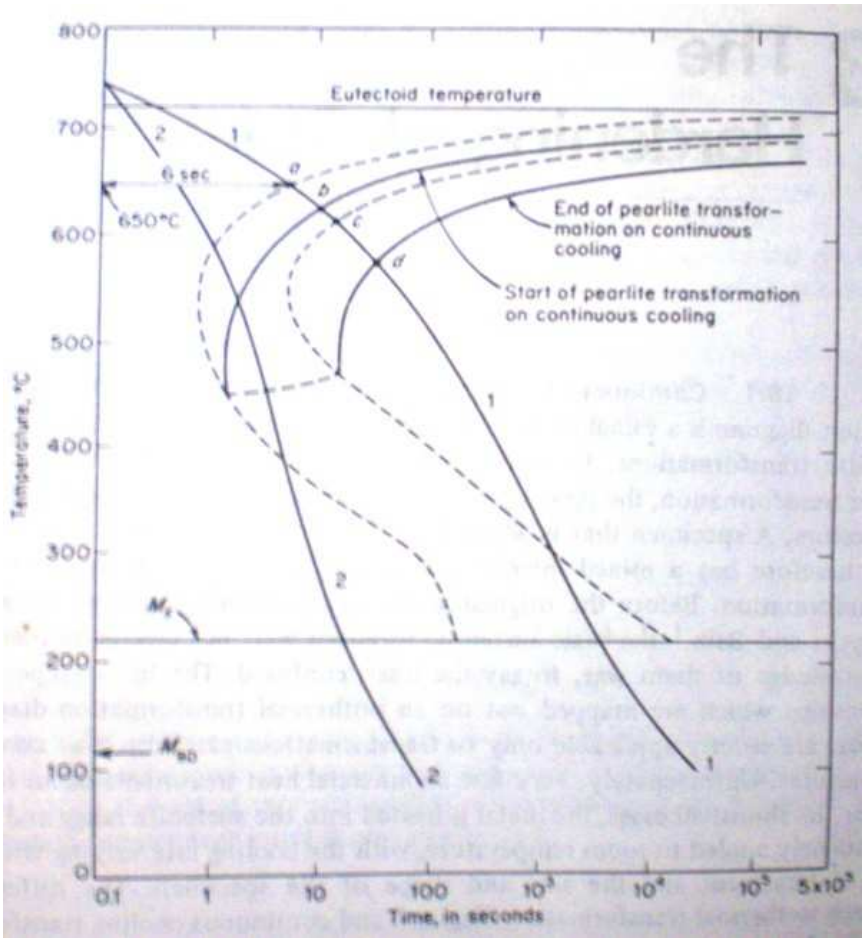
Path 2:- In this case, the specimen is held at 250 ºC for 100 seconds. This is not sufficiently long to form bainite, so that the second quench from 250 ºC to room temperature develops a martensitic structure

Path 3:-An isothermal hold at 300ºC about 500 sec produces a structure composed of half bainite and half martensite. Cooling quickly from this temperature to room temperature results in a final structure of bainite and martensite.

Path 4:-Eight seconds at 600 ºC converts austenite completely to fine pearlite. This constituent is quite stable and will not be altered on holding for a total time of 10^4 sec (2.8 hr) at 600 ºC. This final structure, when cooled to room temperature, is fine pearlite.

2.6 CONTINUOUS COOLING TRANSFORMATIONS.

In almost all cases of heat treatment, the metal is heated into the austenite range and then continuously cooled to room temperature, with the cooling rate varying with the type of the treatment and the shape and size of the specimen. Hence a Continuous Cooling Transformation curve is useful in this perspective which allows us to know the time required for start and end of transformation and the phases obtained under varying rates of cooling. Generally cooling curves are superimposed on the CCT curve to know the effect of cooling rate.



The relationship of the <u>Continuous Cooling diagram to the Isothermal diagram</u> for eutectoid steel.

The difference between isothermal transformation diagrams and continuous cooling diagrams are perhaps most easily understood by comparing the two forms for steel of eutectoid composition as shown above. Two cooling curves, corresponding to different rates of continuous cooling, are also shown. In each case, the cooling curves start above the eutectoid temperature and fall in temperature with increasing times. The inverted shape of these curves is due to plotting of time ordinate according to logarithmic scale.

Now consider the curve marked 1. At the end of approximately 6 sec this curve crosses the line representing the beginning of pearlite transformation. The intersection is marked in the diagram as point ***a.*** The significance of ***a*** is that it represents the time required to nucleate pearlite isothermally at 650ºC. A specimen carried along 1, however only reached the 650ºC isothermal at the end of 6 sec and may be considered to have been at temperatures above 650ºC for the entire 6 sec interval. Because the time required to start the transformation is longer at temperatures above 650ºC than it is at 650ºC, the continuously cooled specimen is not ready to form pearlite at the end of 6 sec.

Approximately, it may be assumed that cooling along path 1 to 650ºC has only a slight greater effect on the pearlite reaction than does an instantaneous quench to this temperature. In other words more time is needed before transformation can begin. Since in continuous cooling there is a drop in temperature, the point at which transformation actually starts lies to the right and below point ***a***. This point is designated by the symbol ***b***. In the same fashion, it can be shown that the finish of the pearlite transformation, point ***d***, is depressed downward to the right of point ***c***, the point where the continuous cooling curve crosses the line representing the finish of isothermal transformation.

The above reasoning explains qualitatively why the Continuous Cooling Transformation lines representing the start and finish of pearlite transformations are shifted with respect to the corresponding isothermal-transformation lines. Thus, the transformation of austentite does not occur isothermally, as assumed in the TTT diagram, but over a certain period during which the temperature drops from, say, T_1 to T_2. The average temperature of the transformation $(T_1 + T_2)/2$ is therefore lower during continuous cooling than during isothermal cooling. As a result, the transformation of austenite will be somewhat delayed. This will cause the TTT curve to be shifted toward lower temperatures and longer transformation times during continuous cooling as compared to isothermal cooling. This type of transformation behaviour is best described by the use of *continuous cooling transformation* (CCT) diagrams. The bainite reaction never appears in this steel during continuous cooling. This is because the pearlite reaction lines extend over and beyond the bainite transformation lines. Thus on slow or moderate rates of cooling (curve 1), austenite in the specimens is converted completely to pearlite before the cooling curve reaches the bainite transformation range. Since the austenite has completely transformed no bainite can form. Alternatively in the curve 2, the specimen is in the bainite transformation range for a short duration of time to allow any appreciable amount of bainite to form. (43)

2.6.1. **Additivity Rule and Continuous Cooling Transformation Kinetics.**

The additivity rule was advanced by Scheil and later, independently by Steinberg (44) to predict the start of transformation under non isothermal conditions. Scheil proposed that the time spent at a particular temperature, t_i, divided by the incubation time at that

temperature, τi, might be considered to present the fraction of the total nucleation time required. When the sum of such fractions (*called the fractional nucleation time*) reaches unity, transformation begins to occur, i.e,

$$\sum_{i=1}^{n} \frac{t_i}{\tau_i} = 1 \quad \text{or} \quad \int_0^t \frac{dt}{\tau(T)} = 1$$

If the concept of Scheil's additivity is extended from the incubation period to the whole range of transformed fraction (from 0 to 100%), the rule of additivity is as follows: given an isothermal TTT curve for the time τx **(T)** as a function of temperature, at which the reaction has reached a certain fractional completion X. Then, on continuous cooling when the integral reaches unity,

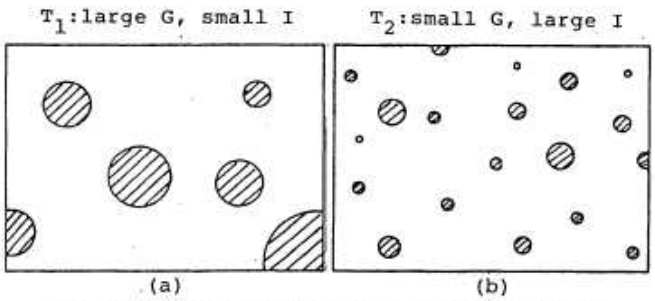
$$\int_{t_e}^{t} \frac{dt}{\tau_X(T)} = \int_{T_e}^{T} \frac{1}{\tau_X(T)} \frac{dt}{dT} \cdot dT = 1$$

the fractional completion will be X. Here for pearlite transformation ***Te*** is the eutectoid temperature and te is the time at which temperature becomes ***Te*** during cooling. It should be noted that additive conditions enables one to calculate the transformed fraction during cooling from the overall isothermal data only, even if the individual growth rates are not known as a function of temperature.

2.6.2. **Conditions for the Transformed Fractions to be Additive**.

Consider the simplest type of cooling transformation obtained by combining two isothermal treatments at temperatures T1 and T2, where T1> T2. Assume that the ratio of the nucleation rate I to the growth rate G is larger at the lower temperature T2. The microstructures which will be produced by the isothermal holding at T1 and T2 are schematically illustrated in Figs. 1(a) and (b), respectively. At temperature T1 , where the relative nucleation rate is slow and the relative growth rate is fast, the microstructure will be consisted of a small number of large nodules. While at temperature T2, where the relative nucleation rate is fast and the relative growth rate is slow, the microstructure will be consisted of large number of small size nodules. Comparison of these two microstructures in Fig. 1 will show that the specimen transformed at temperature T2

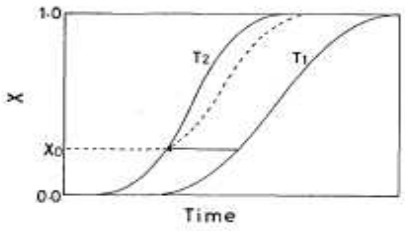
tends to have a large total interface area between austenite and pearlite than that transformed at temperature T1 as long as the shapes of newly formed phases at temperature T1 and T2 are symmetric. Suppose that the specimen is transformed at higher temperature T1 to fraction Xn and is then suddenly cooled to T2. When transformation is continued at T2, the progress of transformation of the specimen initially transformed at T1 must be slower than that transformed at T2 from the beginning, since the former has the smaller total growing interface area than that of the later. The additivity rule will not hold in this case. This situation is schematically illustrated in Fig. 2.



(a) With small nucleation rate and large growth rate
(b) With large nucleation rate and small growth rate

Fig. 1. Schematic microstructures.

Fig 2



Schematic presentation of delay of transformation and deviation from the additivity rule. The specimen is initially held at T_1 for transformation to X_0, whereupon it is cooled suddenly to T_2: the subsequent transformation will be delayed as shown by the broken line because here the additivity rule does no longer apply.

The sufficient condition for the transformed fractions to be additive has been discussed by Avrami**(11)** and Cahn**(44)**. Avrami suggested that the transformed fractions will be additive, over a given range of temperature, if the rate of nucleation is proportional to the rate of growth over that temperature range. Such a reaction is termed as “isokinetic”. The course of an isokinetic reaction is the same at any temperature except for the time scale.

The rule of additivity **(44)** can be stated as follows: given an isothermal ***TTT*** curve for the time τ, as a function of temperature, at which the reaction has reached a certain fraction of completion, x0. Then, on continuous cooling, at that time t and temperature ***T,*** when the integral:-

$$\int \frac{dt}{\tau} = \int \frac{dT}{\tau\left(\frac{dT}{dt}\right)} = \int \frac{dx}{\tau\left(\frac{dx}{dt}\right)} \quad \text{----------(1)}$$

equals unity, the fraction completed will be X_0. The rule has often been stated for the initiation of the reaction. This is a quantity difficult to define, since it depends on the method of observation. It is better to define the time for the initiation as the time for about 1% reaction.

Cahn on the other hand identified that that a reaction is additive whenever the rate is a function only of the amount of transformation and the temperature

$$\frac{dx}{dt} = f(x, T). \quad \text{……. (2)}$$

Then, $\tau = \int_0^{x_0} \frac{dx}{f(x, T)}$ .Upon substitution into (1) and integrating to X_0, one can see that (1) becomes identically unity, showing that equation (2) is a sufficient condition for additivity. The general isokinetic reaction will be defined as a reaction which can be written as:

$$x = F\left(\int h(T)\, dt\right) \quad \text{…… (3)}$$

where ***h(T)*** is a function of temperature only, such as growth rate, nucleation rate, or diffusion constant. It will be convenient to consider X the independent variable, and write (3) as

$$\int h(T)\, dt = H(x). \qquad \text{..... (4)}$$

Then

$$\frac{dx}{dt} = \left[\frac{dH(x)}{dx}\right]^{-1} \cdot h(T)$$

Which satisfies condition (2), and such a reaction will be additive. Cahn noted that a reaction involving two time-temperature parameters will in general not be additive. Nucleation and growth reactions in general involve an integrated growth parameter. However, if the nucleation sites saturate early in a reaction, and if the growth rate is a function of the instantaneous temperature only, the reaction will be additive.

The growth rate under non-isothermal conditions **(44)** may be given as :

$G = G_0\left(1 + \varepsilon \frac{dT}{dt}\right)$ where G_0 the growth is rate under isothermal conditions and ε is a constant.

2.6.3. THE NON ISOTHERMAL RATE LAWS FOR ISOKINETIC REACTIONS.

The amount of transformation expected from an isokinetic reaction for any temperature path can be calculated if *h (T)* and the function F are known. This, however, is not always known. What is known often is τ, and one usually has some clues of the function *F*.

From (4) we can write an expression for *h(T)* in terms of τ:

$$h(T) = \frac{1}{\tau} H(x_0)$$

When this is substituted into (4), it gives an expression account for *H(x)* for non isothermal reactions

$$H(x) = H(x_0) \cdot \int \frac{dt}{\tau}$$

For discontinuous or cellular reactions which saturate, the equations are **(45)**

$$\begin{aligned} x &= 1 - e^{-2SR(t)} \\ &= 1 - e^{-\pi L[R(t)]^2} \\ &= 1 - e^{-4\pi/3N[R(t)]^3} \end{aligned} \qquad \text{---------- (5)}$$

Using (5) H is obtained as:

$$H = \frac{-\ln (1 - x)}{2S}$$

$$H = \left(\frac{-\ln (1 - x)}{\pi L}\right)^{1/2}$$

$$H = \left(\frac{-\ln (1 - x)}{\frac{4\pi}{3} N}\right)$$

respectively for three types of nucleation sites. The amount of transformation can be calculated from

$$\log (1 - x) = \frac{S_n}{S_i} \log (1 - x_0) \int \frac{dt}{\tau}$$

$$\log (1 - x) = \frac{L_n}{L_i} \log (1 - x_0) \left[\int \frac{dt}{\tau}\right]^2$$

$$\log (1 - x) = \frac{N_n}{N_i} \log (1 - x_0) \left[\int \frac{dt}{\tau}\right]^3$$

For grain-boundary nucleated reactions the quantities S_n/S_i, L_n/L_i, and N_n/N_i are easily expressible in terms of grain size.

2.7 EFFECT OF DEFORMATION ON TRANSFORMATION KINETICS.

Deformation can increase the dislocation density and can result in a change in free energy of **γ**, can move up the free energy composition curve. The increase in the chemical potential of **γ**, $\Delta\mu^d$, caused by deformation**(46)** is :-

$\Delta\mu^d = 0.5\mu\rho b^2 V_\gamma$ Where μ and b are shear modulus and Burger's vector, respectively; and ρ is the dislocation density (1/cm^2); V_γ is the molar volume of γ.

2.7.1 Determination of Incubation period.

The incubation period, τ, **(46)** is determined

$$\tau = A \frac{\exp\left[\frac{Q}{RT}\right]}{(\Delta T)^m}$$

where ΔT is the degree of undercooling; and A, Q, and m are the constants related to the alloying composition. For a particular steel grade, these constants can be obtained by experiment

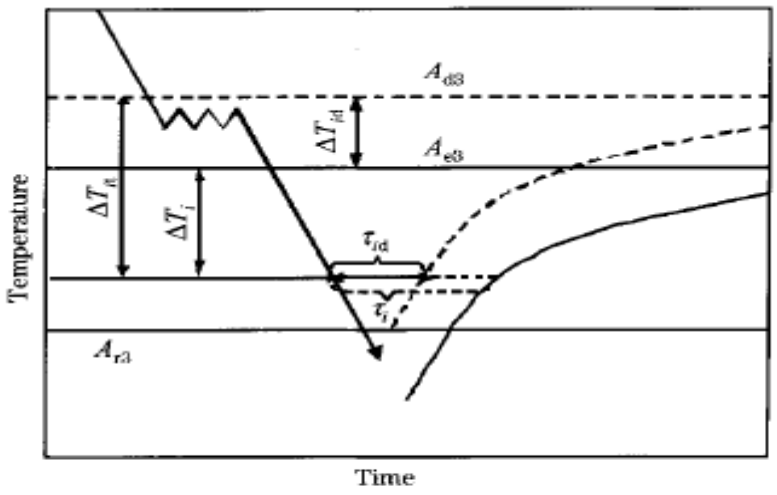


Fig. 1 Diagram depicting incubation period and degree of supercooling under undeformed and deformed conditions

The above figure shows the effect of hot deformation on the incubation period and the degree of undercooling, where, A_{d3}, is the thermodynamic equilibrium temperature of austenite transformation under the effect of deformation. Under no deformation, this temperature is A_{e3}. Deformation can increase the thermodynamic equilibrium temperature and the degree of supercooling. Hence, when deformation occurs, the following equation **(46)** is satisfied:

$$\Delta T_{it} = \Delta T_i + \Delta T_{id}$$

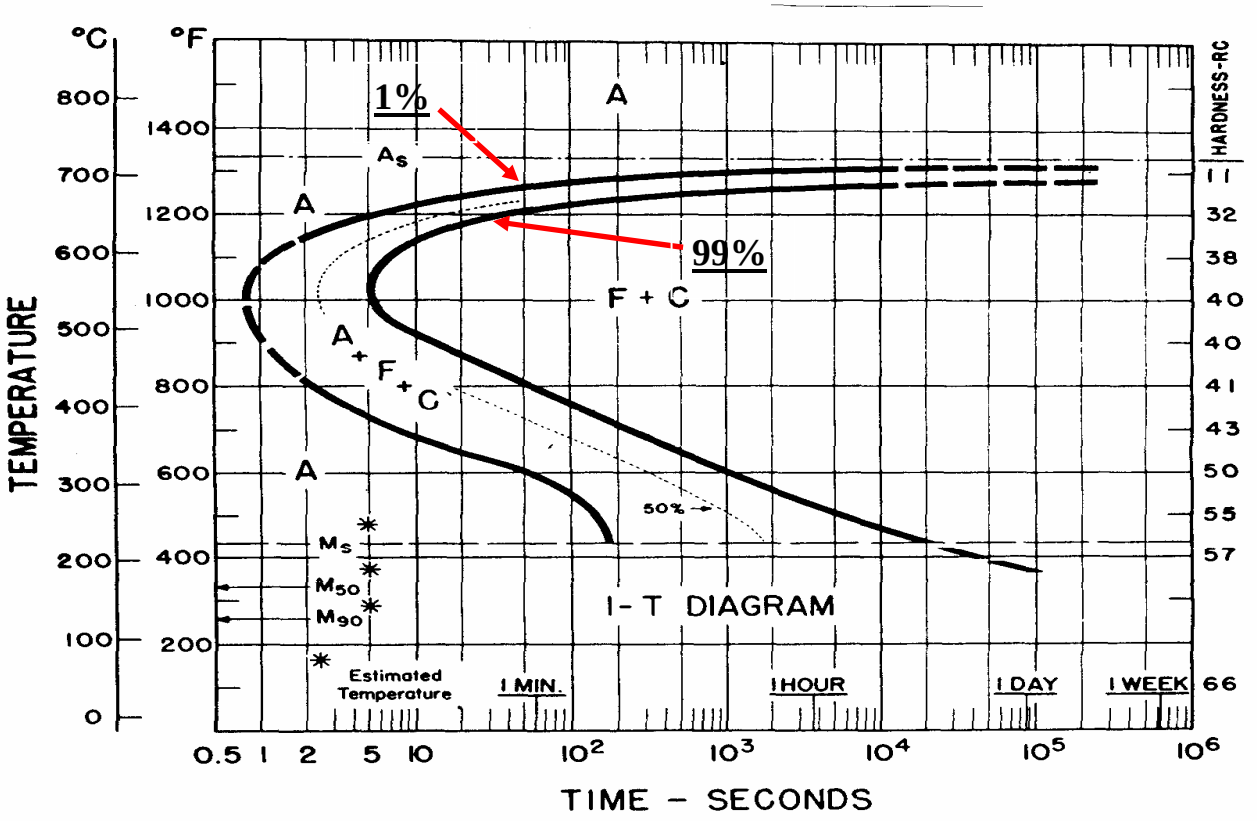
Where ΔT_{it}= Total degree of undercooling.

ΔT_i= Degree of supercooling due to cooling.

ΔT_{id}= Degree of supercooling due to deformation.

3. MODELLING APPROACH.

The modeling approach can be assigned to the determination of transformation data under continuous cooling by using transformation data from isothermal transformation curves. We intend to generate continuous cooling data for Eutectoid (1080) steel. The figure below is an exact copy of the isothermal transformation curve taken from the Atlas of Isothermal Transformation and cooling transformation diagrams (ASM 1977).



Atlas of Isothermal Transformations and Cooling Transformation Diagrams.

ASM (1977).

The start of transformation(1%) and the end of transformation under isothermal conditions is indicated by arrow marks.

Windig 2.5 was used in order to obtain time for start(t_s) and end of transformation(t_f) respectively at a particular temperature(T) correct to 5 places of decimal. The data for 21 different temperature points was plotted in the following format:-

Temperature (^{0}C)	**t_s (in sec)**	**t_f (in sec)**
T1	t1s	t1f
T2	t2s	t2f
T3	t3s	t3f
…	….	….
…	….	….
Tn	tns	tnf

ts=Time for start of transformation of Austenite to Pearlite(F=1%)

tf= Time for end of transformation of Austenite to Pearlite(F=99%)

The **Avrami equation** is given as:

$$F=1-\exp(\ b(T)\ t^{\ n(T)}\ )$$ where ***C(T)*** and ***n(T)*** are temperature dependant factors and θ is the time. For a particular temperature say T1, we can have two equations by substituting T=T1 and θ= t1s and t1f respectively corresponding to which the fraction of austenite transformed is 1% and 99% in the above Avrami equation to find out the value of ***b(T1)*** and ***n(T1).*** Similarly, we can determine the values of ***b(T)*** and ***n(T)*** at different temperatures and record the data. A **C++ program code** was developed in order to compute the values of the same constants. The code is shown as follows.

```
================================================================
======
# include<iostream.h>
# include<conio.h>
# include<math.h>
void main()
{ clrscr();
 long double n[21],b[21],x,y,z,g;
 long double xs=0.01,xf=0.99;int i;
 long                                                    double
t[]={537.7778,427.5278,584.2778,315.5556,286.2722,386.1833,649.7778,682.5,
 634.2222,365.5111,329.3389,300.05,351.73,455.0889,482.6556,
 510.2167,696.2778,372.4056,399.9667,594.6111,567.0556};
 long double ts[]={0.8314,2.1466,1.081,51.633,101.5,5.1548,5.0812,38.788,3,

8.9422,31.286,75.165,14.036,1.4753,1.0931,0.89544,188.39,7.3188,3.7228,1.1839,.8975
1};
 long double tf[]={5.3183,53.185,6.1935,1020.8,2391.7,156.09,38.736,1668.5,18.707,
 264.06,701.16,1602.1,384.44,27.053,13.761,7.1776,50550.0,221.61,109.94,
 7.0238,5.4598};
 for(i=0;i<21;i++)
 {
  x=(log(1-xs)/log(1-xf));y=(ts[i]/tf[i]);;z=log(y);
  n[i]=log(x)/z;
  z=log(1-xs);g=pow(ts[i],n[i]);b[i]=(z/g);
 }
 cout<<"the values of the constants n(T) and b(T) are as follows\n";
 cout<<"T\t\t\tn(T)\t\t\tb(T)\n";
 cout<<"-----------------------------------------------------\n";
 for(i=0;i<21;i++)
```

```
{
 cout<<t[i]<<"\t\t"<<n[i]<<"\t\t"<<b[i]<<"\n\n";
}}
==========================================================
======
```

By using OriginPro 8.0, we plotted the variation of b(T) and n(T) respectively with respect to temperature as shown in fig 1 and fig 2.

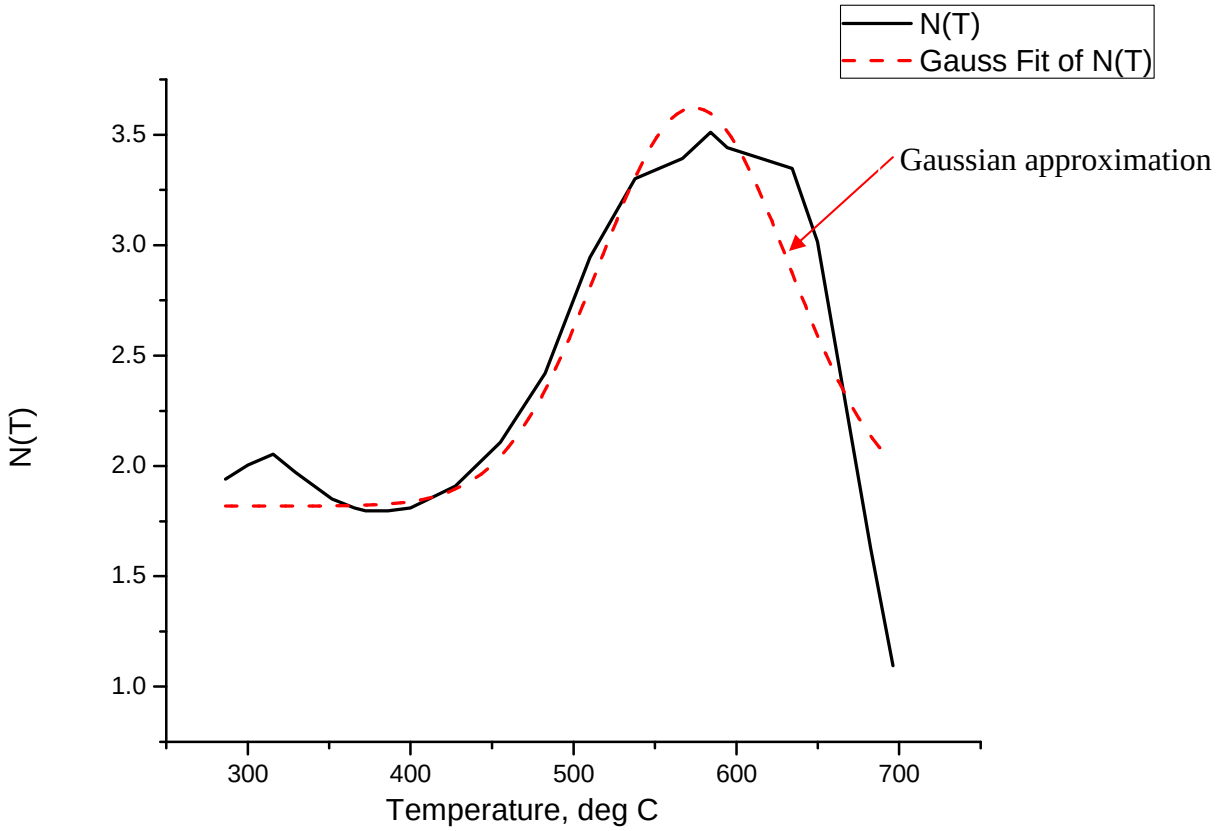


Fig 1. Variation of **n(T)** versus **T.**

A gaussian fit for the plot of n(T) versus T was done to have a good approximation of the actual curve. The equation determined for n(T) is indicated below.

Equation	y=y0 + (A/(w*sqrt(PI/2)))*exp(-2*((x-xc)/w)^2)	
Adj. R-Square	0.80896	
		Value
N(T)	y0	1.81802
N(T)	xc	573.99954
N(T)	w	116.54578
N(T)	A	263.63724
N(T)	sigma	58.27289
N(T)	FWHM	137.22217
N(T)	Height	1.80489

Temperature, deg C

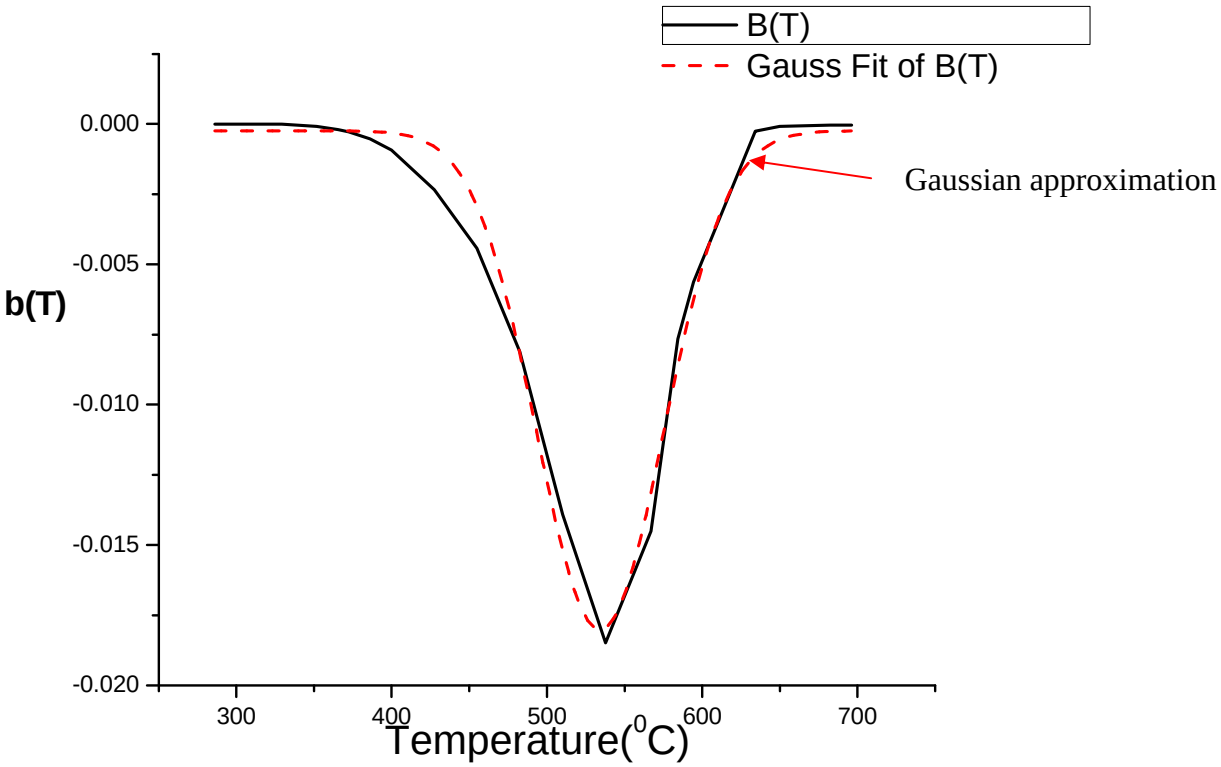


Fig 2. Variation of **b(T)** versus **T**.

In this case too, a gaussian approximation was preffered to have better continuity of the approximated curve with respect to the original one. The equation of b(T) is indicated below.

Equation	y=y0 + (A/(w*sqrt(PI/2)))*exp(-2*((x-xc)/w)^2)	
Adj. R-Square	0.979	
b(T)		Value
B(T)	y0	-2.38148E-4
B(T)	xc	534.27324
B(T)	w	81.51234
B(T)	A	-1.81731
B(T)	sigma	40.75617
B(T)	FWHM	95.97345
B(T)	Height	-0.01779

A C++ program code was again developed in order to determine the transformation data i.e. temperature and time corresponding to start and end of transformation under continuous cooling conditions. This has now become possible after the determination of temperature constants b(T) and n(T) at any temperature.

The algorithm for the program is stated as follows:-

Step 1:- The cooling curve is considered as a series of isothermal steps. Avrami equation was used to determine the fraction of austenite transformed in each isothermal step.

Step 2:- By iteraton method, when the fraction transformed sums= 0.01, time (ts) and temperature (Ps) was noted down. These values correspond to start of transformation.

Step 3:-Similarly, when the fraction transformed sums =0.99, time (tf) and temperature (Pf) was noted down. These values correspond to the end of transformation.

The program code for the determination of transformation data under continuous cooling is as follows.

```
================================================================
======
# include<iostream.h>
#include<conio.h>
#include<math.h>
void main()
```

```
{
 clrscr();
 cout<<"construction of CCT by data obtained from TTT curve\n";
 cout<<"\nentry of the cooling rates\t";long double c; cin>>c;
 int i,k;
 long double as1,af1,ts,tf;long double n,b;
 cout<<"\n define the time limit for isothermal step.==\t";
 long double tend,tlimit,tstart;cin>>tlimit;
 long double a,as,af,xs=0.0,xf=0.0;
 cout<<"\n define the austenising temperature==\t";cin>>a;as=723;af=723;
 long double x,y;

  while(xs<=0.01)
  {k++;
   x=(pow(((as-573.9995)/116.5457),2))*(-2);
   n=1.81802+((263.6372/(116.5457*(sqrt(11/7))))*pow(2.303,x));
   y=(pow(((as-534.27324)/81.51234),2))*(-2);
   b=-0.000238144+((-1.81731/(81.51234*(sqrt(11/7))))*pow(2.303,y));cout<<n<<b;
   xs+=(1-exp(b*pow(tlimit,n)));cout<<"xs=="<<xs;
   as=as-(c*tlimit);cout<<"\t"<<"as=="<<as<<"\n";
  } tstart=tlimit*k;k=0;
  while(xf<=0.999 && as<=723)
  {k++;
   x=(pow(((af-573.9995)/116.5457),2))*(-2);
   n=1.81802+((263.6372/(116.5457*(sqrt(11/7))))*pow(2.303,x));
   y=(pow(((af-534.27324)/81.51234),2))*(-2);
   b=-0.000238144+((-1.81731/(81.51234*(sqrt(11/7))))*pow(2.303,y));cout<<n<<b;
   xf+=(1-exp(b*pow(tlimit,n)));cout<<"xf=="<<xf;
   af=af-(c*tlimit);cout<<"\t"<<"as=="<<as<<"\n";
  }tend=tlimit*k;k=0;
  as1=as;
```

```
 af1=af;
 ts=tstart;
 tf=tend;
 cout<<"\n\nTemp start\tTime start\t Temp end\tTime end";
 cout<<"\n-------------------------------------------------------------\n";
 cout<<as1<<"\t\t"<<ts<<"\t\t"<<af1<<"\t\t"<<tf<<"\n\n";
}
```

==========

======

4. EXPERIMENTAL WORK.

The basis of the experimental work can be strongly assigned to the determination of transformation start temperature [**Ps**] and transformation end temperature [**Pf**] with the time being noted after the austenisation of the experimental eutectoid samples takes place.

Eutectoid rod samples were provided by the **Department of Metallurgy and Materials Engg, N.I.T Rourkela**. From the initial rods being provided, cylindrical samples were machined to have a maximum length of 25mm and a diameter of exactly 8.15 mm. The composition of the samples was determined by **Wet chemical analysis** carried out in the **R&D division, Rourkela Steel Plant.** The exact composition was determined as given the table below:-

Carbon(%)	Manganese(%)	Sulphur(%)	Phosphorous	Chromium(%)	Nitrogen(ppm)
0.81	0.684	0.016	0.024	0.0606	60

4.1 Dilatometric Analysis.

Dilatometric analysis of the eutectoid specimens were carried out in *NETZSCH Dilatometer*.

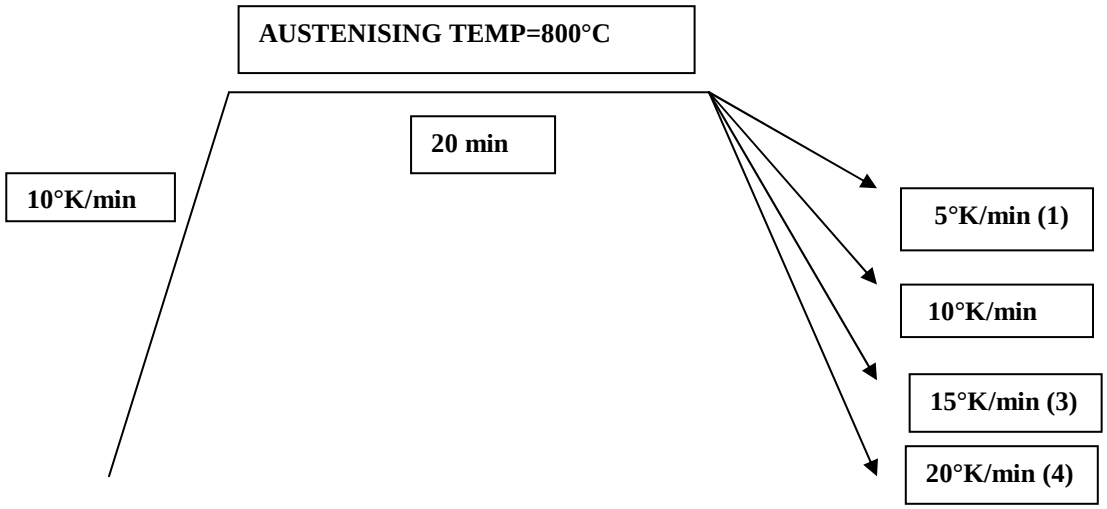
NETZSCH Dilatometer.

Dilatometry is a thermo analytical technique for the measurement of expansion or shrinkage of a material when subjected to a controlled temperature/time program.

Accurate measurement of dimensional changes is required in ceramic research, to measure both thermal expansion of a ceramic, and for carrying out sintering studies on the reactive precursor powders and derivation of activation energies. The dilatometer operates over a temperature range from room temperature to 1600 °C, at heating rates of 0.1 – 50 K/min, with programmable heating, cooling and isothermal sections possible, under either air or a protective atmosphere. It can measure samples up to 25 mm long and with a diameter of up to 12 mm, with a maximum shrinkage/expansion of 5 mm, and to an accuracy of 1.25 nm. The other analysis that can be carried out by this instrument is:-

- Thermal expansion
- Coefficient of Thermal Expansion
- Expansivity
- Volumetric expansion
- Density change
- Sintering temperature and shrinkage steps
- Glass transition temperatures
- Softening points
- Phase transitions
- Influence of additives.

(a) Four eutectoid samples were heated upto 800^0C, with a constant heating rate of 10^0K. After achieving the temperature the samples were austenised for 20 min, and then cooled with varying rates of 5^0K, 10^0K, 15^0K and 20^0K respectively.

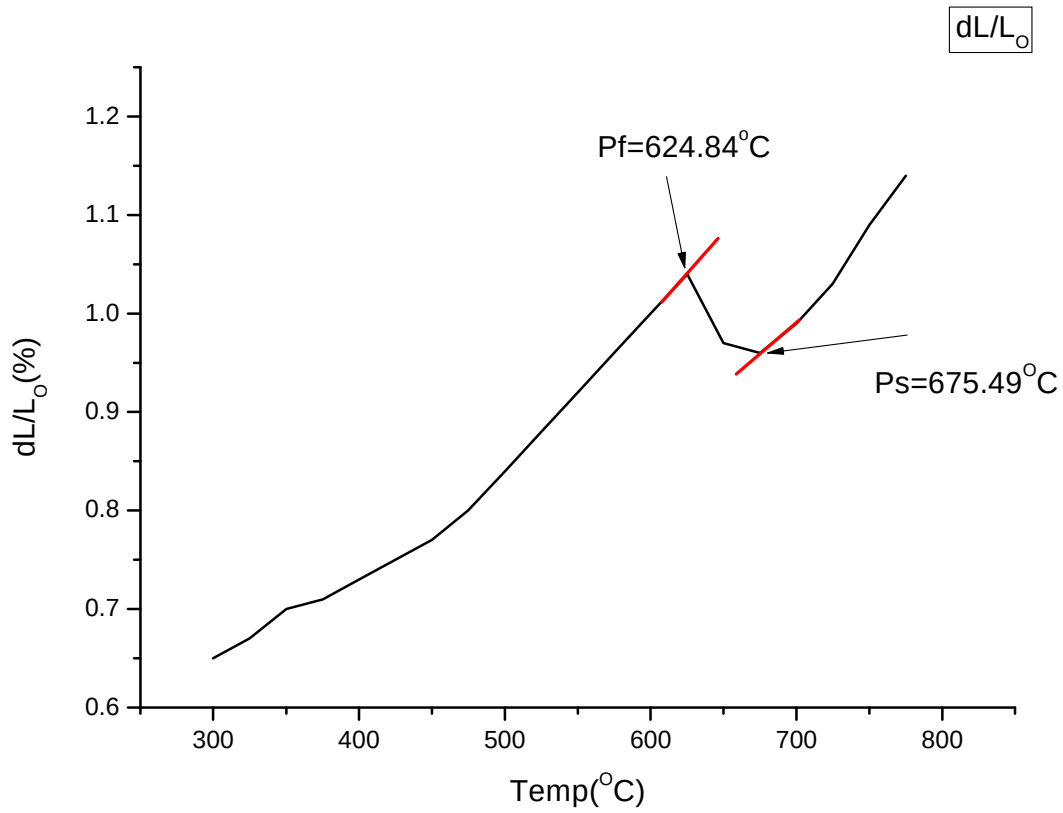


Dilatometry is a technique by which we can determine the transformation temperature by monitoring the dilation of the sample with respect to temperature. When the eutectoid sample is continuously cooled from the austenising temperature. The moment there is a sharp change in dilation, corresponds to the start of austenite to pearlitic transformation. Successively another such point is encountered which corresponds to the end of pearlitic transformation.

5. RESULTS AND DISCUSSION.

The data obtained from NETZSCH Dilatometer was plotted in the form of dilation curves for all the four samples with the use of OriginPro 8.0 i.e. variation of change in length with respect to the original length against temperature. This gives us value of the transformation temperature during austenite to pearlitic transformation when continuously cooled from the austenisation temperature at a specified rate.

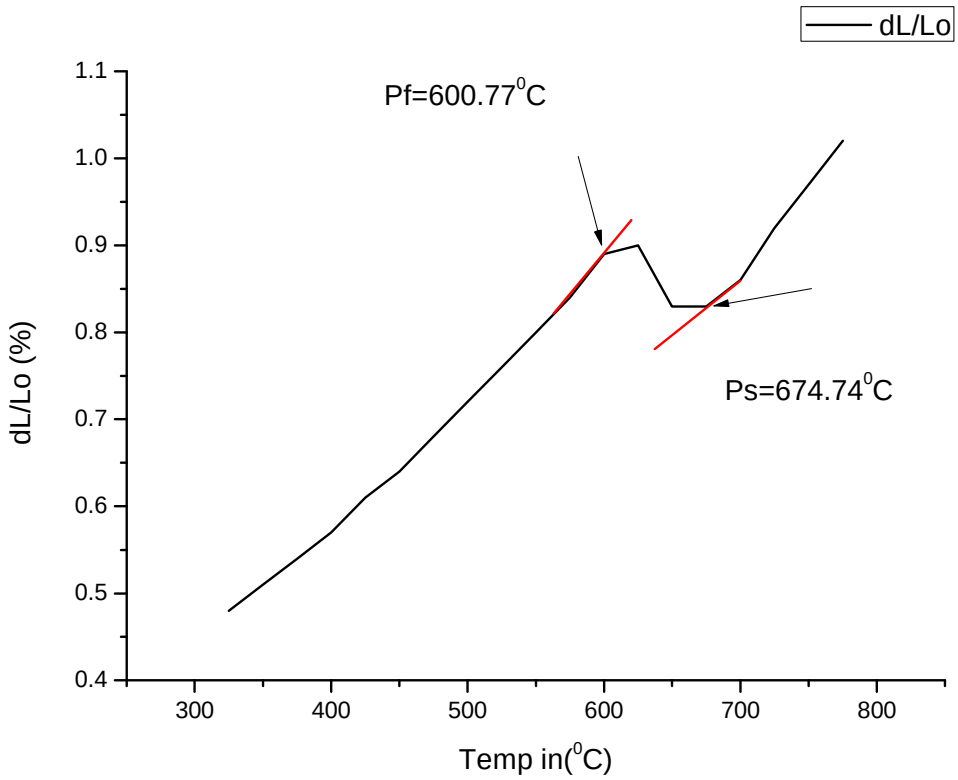
Dilation curve for eutectoid steel austenised at 800^0C for 20 min and cooled at a constant rate of 5^0K.



This dilation curve is a characteristic of austenite to pearlitic transformation when continuously cooled. Ps and Pf denote the start and end of transformation in terms of temperature.

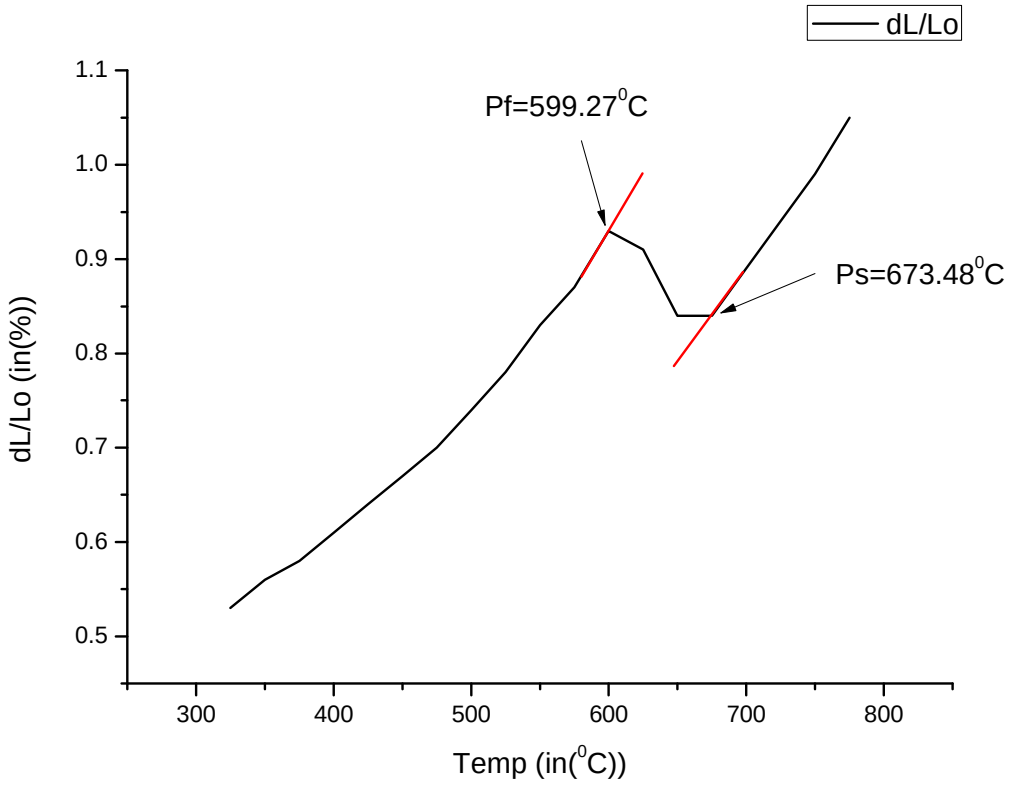
Ps=675.49^{0}C
Pf=624.84^{0}C

Dilation curve for eutectoid steel austenised at 800^0C for 20 min and cooled at a constant rate of 10^0K.



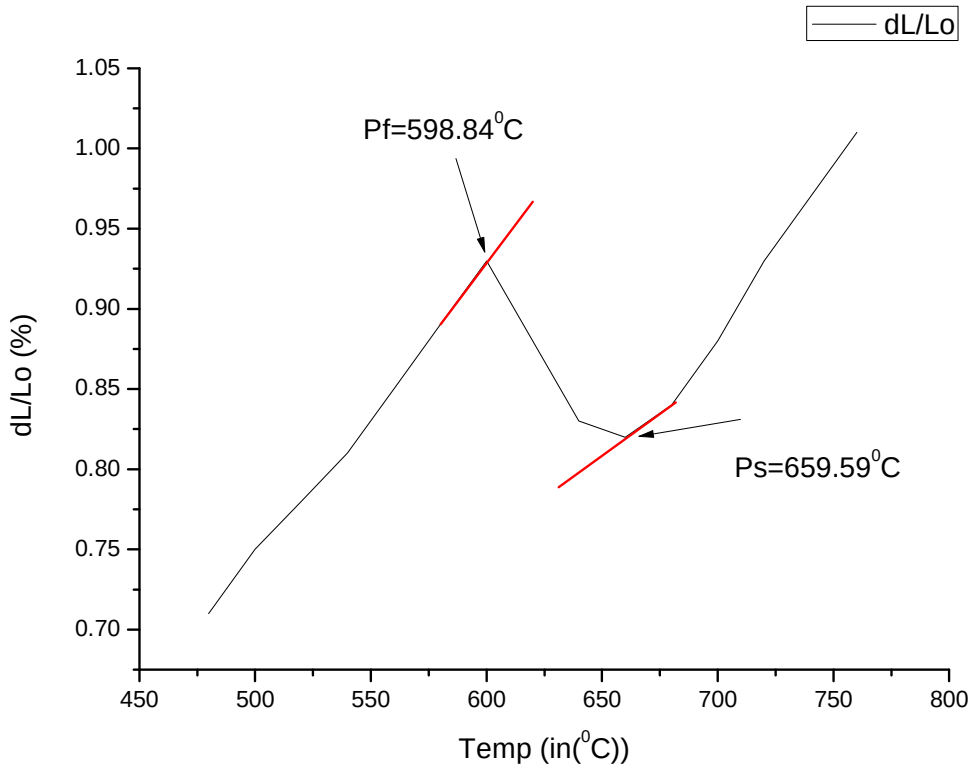
Ps=674.74^{0}C
Pf=600.77^{0}C

Dilation curve for eutectoid steel austenised at 800^{0}C for 20 min and cooled at a constant rate of 15^{0}K.



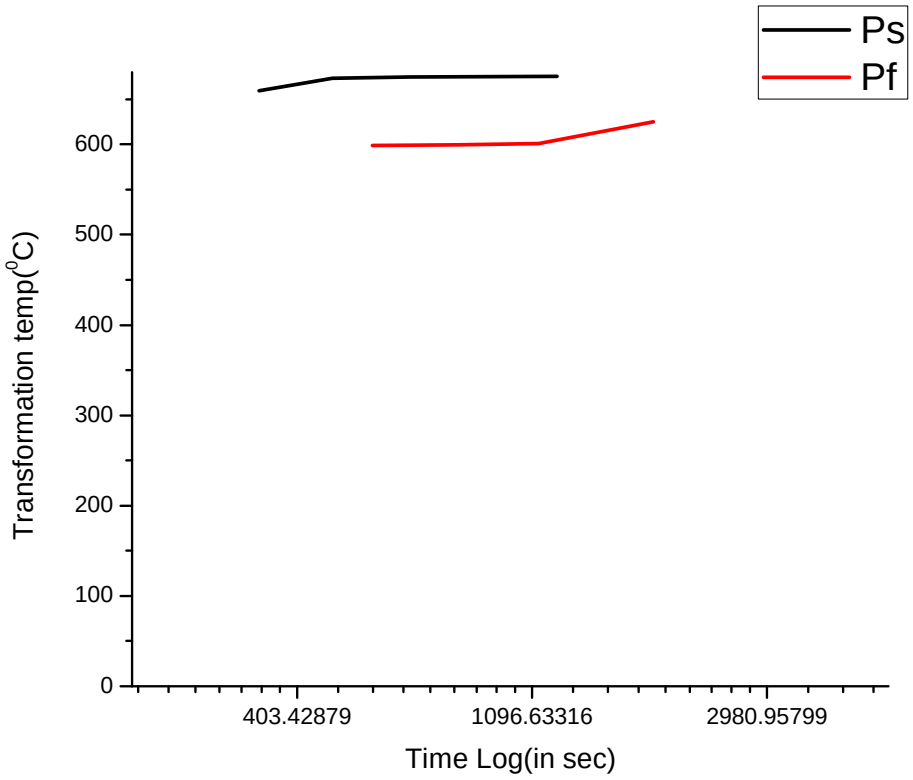
Ps=673.48^{0}C
Pf=599.27^{0}C

Dilation curve for eutectoid steel austenised at 800^{0}C for 20 min and cooled at a constant rate of 20^{0}K.



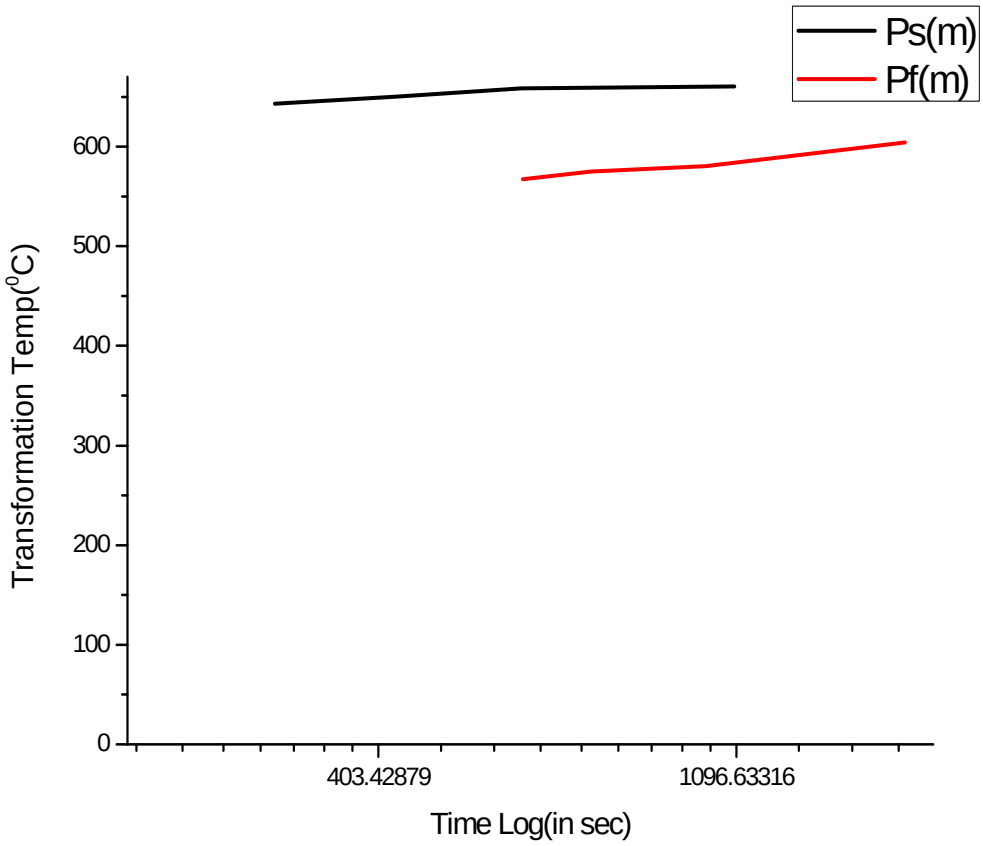
Ps=659.59^{0}C
Pf=598.84^{0}C

Time was also monitored by the dilatometer; hence the time interval can be calculated between the end of austenisation and the start **(ts)** and end **(tf)** of pearlitic transformation respectively under continuous cooling conditions. Hence with the knowledge of **Ps** and corresponding **ts** and **Pf** and corresponding **tf**, for a particular cooling rate, it is possible to plot the data in temperature versus time plot. Similar results can be merged into the plot for varying cooling rates. The plot obtained by using the dilatometry data for four different continuous cooling conditions is shown below.



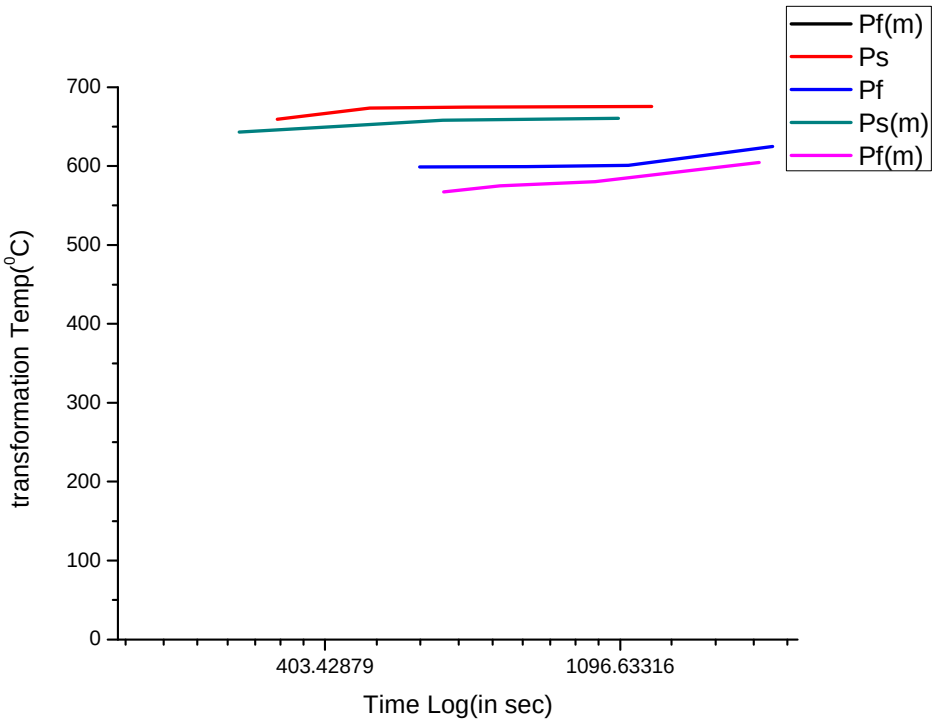
The upper line indicates the start of transformation under continuous cooling conditions and the lower line indicates the end of transformation. This plot also corresponds to the part of CCT curve for Eutectoid steel (1080) under slow cooling conditions.

For the same cooling rates i.e. 5^0K/s, 10^0K/s, 15^0K/s, 20^0K/s, the transformation temperatures (Ps, Pf) and time (ts, tf) was determined using the mathematical model. The results were once again plotted in temperature versus time axis. The plot beneath corresponds to the data obtained from the mathematical model.



This plot is a model of the actual CCT curve for eutectoid (1080) steel. Superimposing the experimental and modeled plots of continuous cooling data gives us a better picture of correlation of the modeled results with the experimental results.

Experimental and Modeled CCT curve superimposed sharing the same axis.



The transformation temperatures determined by the model involving the concept of isothermal steps showed the same variation as the results obtained from the experimental data. The temperatures that denotes the start of transformation; incase of modeled results; were smaller than the corresponding experimental values, within a range of 20-24^{0}C. The temperature which corresponds to the end of transformation varies within the same range with respect to the experimental results. Thus we find that there is a good correlation between the experimental and modeling results since they vary within a narrow range and the plot characteristics for the modeling results being similar with respect to the experimental results.

The discrepancy in the modeling results with respect to the experimental results may be attributed to various factors. Firstly, the cooling characteristics incorporated in the model for determination of transformation characteristics is of **Newtonian type** i.e. the cooling rate is linear with respect to time. However in actual cooling conditions the cooling

characteristics is never the same as earlier assumed case and follows non-linear cooling. The **non-linearity** of the cooling curve may be attributed to factors like heat energy released during transformation, recalescence and limitations of the apparatus. **Recalescence** is a property of any material that possesses the ability to undergo phase transformation, by virtue of which it either releases or absorbs heat during phase transformation. The heat either released or absorbed affects the cooling rate of the sample. This may have contributed to some extent to the discrepancy in the results. Hence modeling of the non-linear cooling curve can lead us one step closer to obtain better results.

The effectiveness of the concept of the **isothermal/isokinetic** steps incorporated during the continuous cooling of the samples may be judged from the fact that it provides us very useful information regarding the transformation data; with the knowledge of data from isothermal transformation characteristics. The basic concept is that, on decreasing the time limit for an individual isokinetic step, we associate maximum number of those steps along the cooling curve. By doing so, we may obtain better approximation of the transformation data with respect to the experimental data. When we associate isokinetic steps with a comparatively slower cooling rate, a maximum number of isokinetic steps can be associated with it and the isokinetic steps can be oriented in a better manner along the path of cooling curve. However, with a faster cooling curve, the isokinetic steps may not be aligned along the path of cooling curve. Hence the concept of isokinetic steps applied to a faster cooling rate may result in improper approximation of the transformation data.

The transformation kinetics of austenite to pearlite transformation is strongly governed by the prior austenitic grain size. The prior austenitic grain size is a function of austenisation temperature and also on the time for austenisation. Higher is the austenisation temperature, greater will be the prior-austenitic grain size. Prior-austenitic grain size is also a direct function of austenisation time but austenisation temperature is the dominant factor. At lower austenising temperatures, the grains being finer have overall longer grain boundary length. Since pearlitic transformation initiates at the grain boundaries, it is obvious that lesser under cooling is required to initiate pearlitic transformation. Similarly at higher austenising temperatures, grains being coarser, overall

grain boundary length is less and hence more under cooling is required to initiate pearlitic transformation. Thus the incorporation of variation of prior-austenitic grain size with austenising temperature and austenisation time may improve the approximation of the modeled data.

6. CONCLUSION.

The concept of isothermal/isokinetic steps in association with the cooling curve that was incorporated in the modeling; for generation of transformation data under continuous cooling conditions provides a better approximation for slower cooling rates. The modeled results showed the similar variation for the transformation data when compared to that of continuous cooling in actual conditions.

For faster cooling rates, the non-association of series of isokinetic steps is a major reason for non approximation of the modeled data with respect to the transformation data under actual cooling conditions.

7. SCOPE FOR FUTURE WORK.

(1.) The continuous cooling curve assumed in this work is of Newtonian type. i.e. linear. However in actual conditions, the cooling curve is of non-Newtonian type. An attempt to model the non-linear cooling curve may result in better approximation of the modeled results when compared to transformation data under actual continuous cooling conditions.

(2.) The start and end of austenite to pearlite transformation is denoted as 1 %(0.01) and 99% (0.99) respectively in TTT and CCT curves in ASM handbook. Correction of these curves can be made by a model which will define the start of transformation as 0.00001% or even lesser. Similarly the end of transformation can be defined as 99.99999% or even more.

(3.) The concept of isokinetic/isothermal steps have to be supplemented with other features so that the prediction of transformation kinetics is possible under faster cooling conditions.

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